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Movement of Lagoon-Liquor Constituents below Four Animal-Waste Lagoons

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ABSTRACT

Movement of liquor constituents from animal-waste lagoons has the potential to degrade ground water quality. The depth of movement and concentrations of lagoon-liquor constituents in the soil underlying three cattle (*Bos taurus*)-waste retention lagoons and one swine (*Sus scrofa*)-waste lagoon were determined. Samples were taken by using a direct-push coring machine, dissected by depth, and analyzed for total N, organic C, $CaCO_3$, pH, cation exchange capacity (CEC), texture, and extractable NO_3, NH_4, P, Cl, Ca, Mg, K, and Na. Ammonium N concentrations were greatest in the upper 0.5 m of soil under all four lagoons with concentrations ranging from 94 to 1139 mg kg^{-1}. Organic N was determined to make up between 39 and 74% of the total N beneath all lagoons. The swine lagoon had 2.4 kg N m^{-2} in the underlying soil whereas the cattle lagoon with highest quantity of N had 1.2 kg N m^{-2} in the underlying soil. Although N concentrations decreased with depth, N was greater than expected background levels at the bottom of some cores, indicating that the sampling efforts did not reach the bottom of the N plume. Nitrate N concentrations were generally less than 5 mg kg^{-1} immediately below the lagoon floor. In the uppermost 0.5 m of soil underlying the swine and three cattle lagoons, NH_4^+ occupied 44% and between 1 and 22% of the soil cation exchange sites, respectively. The depth of movement of N under these lagoons, as much as 4 m, may pose remediation difficulties at lagoon closure.

Lagoons used to store and treat wastes from cattle and swine production facilities are commonly constructed with a compacted soil liner. In the Great Plains, the soil used for the liner may be native or imported to the site to ensure that the post-construction hydraulic conductivity of the liner meets state-imposed guidelines. Measurements of whole-lagoon seepage from actively used lagoons have tended to be between 0.2 and 2.4 mm d^{-1} (Glanville et al., 2001; Ham, 1999, 2002; Ham and DeSutter, 1999, 2000). Thus, soil liners are not impermeable barriers to the downward movement of lagoon-liquor constituents. Although virtually no NO_3–N has been detected in swine- or cattle-lagoon liquor (Barker et al., 2001; DeRouchey et al., 2002; Ham, 2002; Ham and DeSutter, 1999, 2000), predicted NH_4–N losses have been as much as 0.5 and 0.05 kg m^{-2} yr^{-1} from a swine and cattle lagoon, respectively (Ham and DeSutter, 2000). Thus, the potential for large quantities of NH_4–N to move into the underlying subsoil during the life span of the operation is great. Ammonium N was reported to bethe strongest indicator of lagoon seepage from field investigations by Huffman and Westerman (1995). Organic N concentrations can also be great under lagoons, and have been reported to make up between 19 and 44% of the total N under swine and cattle lagoons, respectively (Ham, 2002). Although the downward movement of both NH_4–N and organic N into the subsoil poses little immediate environmental risk, the conversion to NO_3–N through mineralization and nitrification could increase ground water NO_3–N to concentrations in excess of the drinking water standard (USEPA, 2002). The likelihood of this scenario would increase if the manure additions to the lagoon were to cease and the soil/liner became aerobic.

Studies have been conducted to determine the movement of lagoon-liquor constituents from animal-waste lagoons by using soil-sampling techniques (Baker et al., 2000; Culley and Phillips, 1989; Ham, 2002; Ham and DeSutter, 2000; Huffman and Westerman, 1995; Maule and Fonstad, 1996; Miller et al., 1976; Parker et al., 1995; Perschke and Wright, 1998) and by using soil water and ground water sampling (Cates, 1983; Ciravolo et al., 1979; Huffman, 2004; Westerman et al., 1995; Withers et al., 1998). Of these, only the Ham (2002), Ham and DeSutter (2000), and Parker et al. (1995) studies investigated lagoons located in the Great Plains, which is an increasingly popular region for raising livestock (Ham and DeSutter, 2000). Parker et al. (1995) investigated the soil under a 22-yr-old cattle-waste lagoon in Nebraska and determined that NH_4–N, NO_3–N, organic N, K, SO_4–S, Bray P, and Cl had moved into the underlying subsoil. Concentrations of these constituents were generally greater near the surface and decreased with depth. They also exhibited great variability throughout the lagoon. Ham and DeSutter (2000) showed similar results for NH_4–N from a swine-waste lagoon, cattle-waste lagoon, and dairy-waste lagoon in Kansas but did not address the variability one may expect to encounter. Ham (2002) indicated that there was inherent variability of NH_4–N, P, and Cl throughout a cattle lagoon in Kansas, with concentrations greatest near the surface and decreasing with depth. The spatial variability of the downward movement of chemicals from lagoons will depend on static waste ponding resulting from construction techniques, preferential flow pathways through the liner and underlying subsoil (Ciravolo et al., 1979; McCurdy and McSweeney, 1993), and heterogeneity of the liner material.

Lagoons are generally constructed below ground level by excavating between 3 and 6 m of soil (Ham and DeSutter, 2000). Depending on whether the liner was constructed with native or imported soil, the subsoil may have quite different physical and chemical characteristics than the actual liner material. Once the lagoon liquor travels beyond the constructed soil liner, CEC and clay content in the soil will likely influence further

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Abbreviations: CEC, cation exchange capacity; SEM, standard error of the mean.

downward movement of liquor constituents. Undesirable subsoils would be those having greater sand concentrations and smaller CEC values than the soils used to construct the compacted soil liner (Ham and DeSutter, 2000). To help protect ground water quality, Ham and DeSutter (2000) proposed that a 3-m depth below the proposed lagoon floor should be assessed for CEC and clay content before lagoon construction to minimize potential contamination from liquor constituents. Thus, evaluation of the liquor constituents beneath animal waste lagoons and the depth of their movement will help further assess the environmental risks that are inherent when constructed soil lagoons are used to contain animal wastes. The objectives of this study were to (i) determine the concentrations and extent of movement of N, C, P, Cl, Ca, Mg, K, and Na beneath four animal-waste retention lagoons in Kansas and (ii) investigate the soil characteristics underlying these lagoons.

MATERIALS AND METHODS

This study investigated the soil beneath four animal-waste lagoons located in Kansas. The cattle lagoons will hereafter be referred to as Cattle 1, Cattle 2, and Cattle 3. Cattle 1 was an 11-yr-old cattle-waste retention lagoon located in southwestern Kansas and had a surface area of 1.8 ha. Cattle 2 was a 30-yr-old cattle-waste retention lagoon located in west-central Kansas and had a surface area of 1.5 ha. Cattle 3 was a 17-yr-old cattle-waste retention lagoon and the swine lagoon was a 25-yr-old, decommissioned swine-waste lagoon. Cattle 3 and the swine lagoon were located in central Kansas and had surface areas of approximately 0.1 ha. During the time of the investigations, Cattle 1 and Cattle 2 were cleared or void of any liquid or sludge layer due to future reconstruction or dry weather, and liquid waste had not entered either of these lagoons within two months before sampling. A thick sludge layer was present (greater than 0.6 m) in Cattle 3 and the swine lagoon for an undetermined amount of time until 24 to 48 h at which time the sludge was removed to allow soil sampling. Construction documents for these lagoons were not available and thus the installation of an engineered, compacted-soil liner was not known. Depth to ground water was recorded from the nearest Kansas Geological Survey well during the time of lagoon sampling. Depth to ground water was greater than 61 m under Cattle 1 and Cattle 2 and for Cattle 3 and the swine lagoon was about 3 and 7 m, respectively.

Soil sampling was performed using a direct-push coring machine (LWW; Concord Environmental Equipment, Hawley, MN) equipped with a 4.6-cm-i.d. sampling tube (D10006P; Concord Environmental Equipment) and single-use polyethylene terephthalate copolymer plastic liners (1024151; Concord Environmental Equipment). Each lagoon was divided into four equally sized sections before sampling, and one core was taken from the center of each section. The surface soils of all lagoons were dry when sampling occurred. A soil sample was not taken outside of the lagoon area for comparative purposes. Cores were transported to Kansas State University, Manhattan, KS, and frozen until they were dissected into 10- to 30-cm intervals. After dissection, soil was oven-dried at 50°C for 24 h and ground to pass through a 2-mm sieve. Oven-dried samples were stored in closed, plastic containers until analyses were performed.

Oven-dried samples were used for all analyses. Samples were analyzed for total N, total C, organic C, $CaCO_3$, pH, and extractable NH_4–N, NO_3–N, Cl, Olsen P, Ca, Mg, K, and Na. Total N was determined by combustion (CN2000; LECO, St. Joseph, MI), and NH_4–N and NO_3–N were extracted from soil by using 1 *M* KCl and analyzed with an autoanalyzer (Alpkem, Clackamas, OR). Ammonium N and NO_3–N were determined by the salicylate–hypochlorite (Crooke and Simpson, 1971) and the Griess–Iiosvay (Keeney and Nelson, 1982) methods, respectively. Organic N was determined to be the difference between total N and the sum of the inorganic N species. Ammonium N analysis on oven-dried soil (55°C) has been reported to overestimate actual exchangeable NH_4–N above that reported for field-moist soil (Nelson and Bremner, 1972).

Total C was determined by combustion (CN2000), and organic C was determined by combustion (CN2000) after removal of carbonates by treatments with 1.2 *M* HCl and water (v/v) until effervescence ceased. Concentration of carbonate was determined by taking the difference in the treated and untreated C values and dividing by 0.12. Chloride was extracted with 0.1 *M* $Ca(NO_3)_2$, determined colorimetrically using the mercury (II) thiocyanate method (Adriano and Doner, 1982), and was analyzed with an Autoanalyzer II (Technicon Industrial Systems, Tarrytown, NY).

Extractable P was determined according to the Olsen sodium-bicarbonate (Olsen et al., 1954) and ascorbic-acid reducing methods (Watanabe and Olsen, 1965) and was analyzed with a spectrophotometer (DU-64; Beckman Instruments, Fullerton, CA). Calcium, Mg, K, and Na were extracted by using a modified procedure of Suarez (1996), in which 5 g of soil was extracted with 25 mL of 1 *M* NH_4OAc, which was adjusted to pH 7.0. The soil–NH_4OAc mixture was shaken for 30 min and centrifuged at a relative centrifugal force of $1136 \times g$ for 20 min and Ca, Mg, K, and Na were determined using inductively coupled plasma–atomic emission spectroscopy (Accuris 141; Fisons Instruments, Beverly, MA).

Cation exchange capacity (CEC) was determined by using the NH_4OAc mechanical-vacuum extractor method outlined in Sumner and Miller (1996), and NH_4–N in the leachate was analyzed by the salicylate–hypochlorite method (Crooke and Simpson, 1971). Soil pH was determined by using a 1:1 mixture of soil and deionized water. The sand and clay fractions were determined with a modified hydrometer method outlined in Gee and Bauder (1986). The clay fraction was determined by taking a hydrometer reading at the specified time after mixing, based on room temperature, and the sand fraction was determined by gravimetric methods. Silt was determined to be the difference between 1000 g kg^{-1} and the sum of the clay and sand fractions.

For each lagoon, the mass of each N species (total N, NH_4–N, and NO_3–N) was determined at each depth increment assuming a constant bulk density of 1300 kg m^{-3} (Ham and DeSutter, 1999) and total masses of each N species per area (g m^{-2}) were determined by summation. Bulk densities from each lagoon may have deviated from this assumed value and could be greater if a constructed soil liner was installed. Some of the coring results were previously presented in Ham (2002) or Ham and DeSutter (2000) and are included in the datasets presented in this paper. The results in Ham and DeSutter (2000) were of a single core from a cattle and swine lagoon, which correspond to Cattle 1 and the swine lagoon in this paper, respectively. The information provided in Fig. 5a, 5b, and 5e of Ham (2002) describes single core results of NH_4–N and organic N from Cattle 1, Cattle 2, and the swine lagoon, respectively. Furthermore, Fig. 6 of Ham (2002) describes NH_4–N, P, Cl, and CEC profiles from four cores of Cattle 1. A more detailed investigation of the chemical and physical characteristics of the soil underlying these lagoons, as described in the aforementioned paragraphs, is presented here.

Table 1. Lagoon liquor constituent profiles beneath an 11-yr-old, 1.8-ha cattle-feedlot runoff lagoon (Cattle 1) located in Kansas.

Depth†	Organic C	$CaCO_3$	Olsen P	Cl	Total N	NO_3–N	NH_4–N	NH_4	Ca	Mg	K	Na	CEC‡
m	g kg^{-1}		mg kg^{-1}					cmol$_c$ kg^{-1}					
0.15	5.2 (3.4)§	147.5 (41.0)	71.2 (24.5)	8 (3.9)	567 (146)	17.1 (13.3)	378 (117)	2.7 (0.8)	23.6 (2.3)	2.8 (0.4)	2.9 (0.7)	0.6 (0.1¶)	10.5 (1.9)
0.45	0.9 (0.1¶)	191.1 (42.4)	28.6 (10.8)	14 (6.8)	402 (90)	4.4 (1.3)	271 (77)	1.9 (0.6)	22.9 (1.9)	4.0 (1.5)	2.2 (0.5)	0.6 (0.1¶)	10.7 (2.3)
0.75	0.8 (0.1¶)	157.8 (54.0)	21.6 (9.9)	15 (7.5)	295 (46)	2.5 (0.1¶)	177 (54)	1.3 (0.4)	23.3 (1.5)	4.3 (1.7)	1.8 (0.5)	0.6 (0.1¶)	9.4 (1.8)
1.05	1.0 (0.3)	96.1 (36.0)	22.2 (9.5)	20 (10.0)	290 (89)	2.5 (0.4)	171 (58)	1.2 (0.4)	21.2 (1.7)	3.7 (1.4)	1.6 (0.5)	0.5 (0.1¶)	8.4 (2.4)
1.35	0.9 (0.2)	155.0 (34.7)	37.5 (8.6)	20 (9.8)	333 (77)	2.7 (0.3)	198 (52)	1.4 (0.4)	23.3 (2.3)	3.4 (0.9)	1.9 (0.4)	0.6 (0.1¶)	9.0 (2.1)
1.65	0.6 (0.1¶)	111.1 (31.8)	12.2 (5.4)	19 (9.3)	105 (39)	3.1 (0.6)	57 (29)	0.4 (0.2)	19.1 (4.8)	3.6 (1.7)	1.1 (0.4)	0.5 (0.1¶)	8.3 (2.2)
1.95	0.6 (0.1¶)	141.1 (21.9)	9.6 (5.0)	20 (9.8)	140 (38)	2.4 (0.2)	76 (34)	0.5 (0.2)	22.9 (1.8)	3.8 (1.5)	1.2 (0.4)	0.5 (0.1¶)	8.4 (1.8)
2.25	0.7 (0.1¶)	136.7 (42.9)	18.9 (6.4)	17 (9.9)	287 (18)	2.3 (0.3)	174 (19)	1.2 (0.1¶)	21.7 (0.5)	4.7 (1.5)	1.9 (0.5)	0.5 (0.1¶)	8.3 (1.8)
2.55	0.6 (0.1¶)	60.7 (20.4)	26.0 (8.7)	13 (7.5)	267 (15)	3.0 (0.6)	171 (16)	1.2 (0.1¶)	19.6 (1.0)	4.7 (1.1)	1.5 (0.3)	0.5 (0.1¶)	7.6 (1.2)
2.85	0.4 (0.1¶)	83.8 (16.6)	3.9 (1.1)	13 (6.5)	70 (14)	2.3 (0.2)	20 (10)	0.1 (0.1¶)	27.7 (3.8)	5.9 (2.5)	0.8 (0.1¶)	0.7 (0.2)	8.8 (1.8)
3.15	0.4 (0.1¶)	89.4 (10.5)	5.5 (1.6)	3 (1.5)	63 (16)	2.5 (0.1¶)	24 (15)	0.2 (0.1¶)	23.7 (1.4)	4.1 (1.3)	0.8 (0.1¶)	0.6 (0.1¶)	8.2 (1.6)
3.45	0.4 (0.1¶)	56.7 (18.9)	8.3 (1.9)	6 (3.3)	107 (23)	2.6 (0.1¶)	45 (19)	0.3 (0.1¶)	22.3 (1.7)	3.3 (1.3)	0.9 (0.2)	0.5 (0.1¶)	8.1 (1.7)
3.75	0.3 (0.1¶)	30.2 (8.4)	9.3 (3.4)	11 (5.4)	73 (28)	2.4 (0.1¶)	42 (15)	0.3 (0.1¶)	20.0 (0.8)	2.9 (1.2)	0.7 (0.2)	0.5 (0.1¶)	5.0 (1.0)
4.05	0.2 (0.1¶)	16.0 (4.5)	4.8 (1.9)	13 (6.4)	80 (16)	2.5 (0.1¶)	33 (16)	0.2 (0.1¶)	16.5 (3.4)	3.6 (1.2)	0.7 (0.2)	0.5 (0.1¶)	6.0 (0.8)
4.35	0.3 (0.1¶)	8.3 (6.5)	3.5 (1.0)	18 (8.7)	70 (9)	2.2 (0.1¶)	25 (12)	0.2 (0.1¶)	9.7 (3.5)	3.9 (1.6)	0.6 (0.1¶)	0.5 (0.1¶)	7.4 (2.1)

† Average depth of dissected core beneath the lagoon floor.
‡ Cation exchange capacity.
§ Numbers in parentheses represent the standard errors of the mean (SEM).
¶ Value ≤ 0.1.

RESULTS AND DISCUSSION

Soil Characterization

Because of the nature of the soils underlying the lagoons and the limitations of the coring equipment, not all lagoons were sampled to the same depth. The lagoon floor was considered the top of the sampling depth, 0 m. The lowermost sampling depths of Cattle 1, Cattle 2, Cattle 3, and the swine lagoon were 4.35, 3.75, 1.65, and 3.15 m, respectively (Tables 1–4, respectively). Depth of sampling was limited by high concentrations of sand (>700 g kg^{-1}) in the cattle lagoons and a high clay concentration (>950 g kg^{-1}) in the swine lagoon (Fig. 1). Clay concentrations decreased in the uppermost 1 m of soil under all lagoons with the only increase in clay concentration below the 1-m soil depth occurring under the swine lagoon. Given that these lagoons were not located in the same geographic areas of Kansas, the variability in the properties of the soils underlying these lagoons is not unexpected. Miller et al. (1976) also acknowledged the variability of soil textures underlying animal-waste lagoons and further recommended that lagoons not be built over medium- or coarse-textured soils. However, Huffman (2004) determined that the soil textures in the uppermost 1.5 m of soil underlying lagoons were not good indicators of lagoon seepage characteristics.

The CEC values from all the samples under all of the

Table 2. Lagoon liquor constituent profiles beneath a 30-yr-old, 1.5-ha cattle-feedlot runoff lagoon (Cattle 2) located in Kansas.

Depth†	Organic C	$CaCO_3$	Olsen P	Cl	Total N	NO_3–N	NH_4–N	NH_4	Ca	Mg	K	Na	CEC‡
m	g kg^{-1}		mg kg^{-1}					cmol$_c$ kg^{-1}					
0.05	3.0 (0.6)§	86.9 (9.7)	131.0 (46.6)	147 (34)	785 (213)	40.3 (24.8)	361 (144)	2.6 (1.0)	15.3 (4.1)	4.5 (1.4)	11.2 (2.4)	0.9 (0.3)	20.8 (1.2)
0.15	2.4 (0.4)	69.8 (13.9)	52.5 (20.0)	129 (24)	560 (208)	21.2 (18.1)	259 (132)	1.9 (1.0)	15.3 (3.4)	4.9 (1.8)	10.5 (1.8)	0.8 (0.2)	20.0 (1.7)
0.25	2.5 (0.4)	55.3 (17.2)	33.8 (18.9)	139 (32)	534 (207)	9.3 (5.8)	241 (133)	1.7 (1.0)	16.1 (3.7)	5.6 (2.3)	11.2 (2.1)	0.9 (0.2)	21.7 (1.4)
0.35	2.3 (0.4)	55.0 (11.2)	30.0 (15.1)	140 (33)	517 (192)	6.3 (3.0)	226 (125)	1.6 (0.9)	16.7 (3.7)	6.0 (2.3)	10.1 (2.1)	1.1 (0.2)	22.0 (1.0)
0.45	2.3 (0.3)	55.3 (7.3)	29.1 (15.6)	128 (27)	479 (173)	4.2 (2.3)	210 (115)	1.5 (0.8)	17.6 (3.8)	6.3 (2.0)	8.2 (2.0)	1.2 (0.1¶)	21.3 (1.0)
0.55	2.2 (0.3)	53.5 (7.6)	29.5 (16.1)	119 (22)	429 (149)	2.9 (1.4)	173 (101)	1.2 (0.7)	19.4 (4.0)	6.7 (2.1)	5.6 (1.9)	1.3 (0.2)	20.0 (1.2)
0.65	2.0 (0.3)	47.3 (7.1)	26.2 (15.5)	118 (18)	353 (153)	1.5 (0.5)	127 (98)	0.9 (0.7)	19.3 (3.4)	6.0 (1.9)	4.1 (2.0)	1.3 (0.2)	20.5 (1.8)
0.75	2.2 (0.6)	53.0 (7.7)	45.4 (33.8)	113 (24)	380 (221)	6.1 (2.9)	147 (132)	1.1 (0.9)	18.4 (2.8)	5.1 (1.3)	3.9 (1.9)	1.2 (0.1¶)	17.9 (2.5)
0.85	1.5 (0.4)	46.2 (10.9)	23.8 (14.4)	99 (32)	270 (153)	1.0 (0.1¶)	104 (95)	0.7 (0.7)	16.4 (1.9)	3.6 (0.9)	2.7 (1.4)	0.9 (0.1¶)	15.0 (3.6)
0.95	1.2 (0.4)	40.9 (13.4)	20.0 (13.0)	80 (29)	202 (125)	1.0 (0.2)	82 (76)	0.6 (0.6)	15.3 (1.1)	3.1 (0.8)	2.2 (1.1)	0.8 (0.1¶)	12.3 (3.3)
1.05	1.2 (0.3)	36.0 (10.5)	14.8 (8.1)	75 (23)	234 (122)	0.5 (0.1¶)	71 (66)	0.5 (0.5)	14.3 (1.1)	2.7 (0.5)	1.7 (0.8)	0.7 (0.1¶)	10.8 (2.6)
1.15	1.0 (0.2)	24.7 (4.0)	11.3 (5.2)	62 (12)	102 (39)	0.7 (0.1¶)	28 (25)	0.2 (0.2)	14.1 (2.4)	2.7 (0.9)	1.1 (0.3)	0.6 (0.1¶)	8.1 (1.0)
1.25	0.6 (0.2)	15.7 (1.4)	9.4 (6.1)	48 (17)	64 (48)	0.6 (0.1¶)	29 (27)	0.2 (0.2)	12.0 (2.2)	1.8 (0.7)	0.9 (0.3)	0.4 (0.1¶)	5.9 (0.6)
1.35	0.5 (0.1¶)	17.6 (2.4)	12.1 (5.8)	56 (16)	47 (29)	1.1 (0.6)	31 (25)	0.2 (0.2)	12.1 (2.5)	2.0 (0.8)	1.1 (0.4)	0.4 (0.1¶)	5.8 (0.8)
1.45	0.5 (0.1¶)	19.8 (3.5)	7.3 (3.7)	60 (17)	42 (24)	0.5 (0.1¶)	21 (18)	0.2 (0.1¶)	12.9 (3.2)	2.3 (1.3)	0.9 (0.3)	0.5 (0.1¶)	6.5 (0.6)
1.55	0.6 (0.1¶)	24.4 (5.0)	9.2 (3.6)	65 (13)	44 (7)	1.0 (0.3)	18 (13)	0.1¶ (0.1¶)	13.8 (3.4)	2.9 (1.5)	1.1 (0.3)	0.5 (0.2)	7.1 (0.8)
1.65	0.6 (0.2)	29.7 (9.5)	5.5 (1.1)	65 (11)	50 (10)	0.6 (0.1¶)	12 (8)	0.1¶ (0.1¶)	12.6 (4.0)	2.7 (1.1)	0.9 (0.2)	0.5 (0.1¶)	7.6 (1.6)
1.75	0.7 (0.2)	25.3 (8.1)	4.8 (1.1)	68 (17)	48 (24)	0.6 (0.2)	13 (7)	0.1¶ (0.1¶)	13.1 (4.0)	2.4 (0.8)	0.8 (0.1¶)	0.5 (0.2)	6.5 (1.6)
1.85	0.6 (0.2)	21.7 (8.5)	3.7 (1.1)	59 (18)	34 (18)	0.8 (0.2)	9 (7)	0.1¶ (0.1¶)	12.7 (4.0)	1.9 (0.8)	0.6 (0.1¶)	0.4 (0.1¶)	5.8 (1.9)
1.95	0.4 (0.1¶)	16.1 (5.7)	2.4 (0.5)	51 (10)	21 (10)	0.4 (0.1¶)	7 (5)	0.1¶ (0.1¶)	11.2 (3.8)	1.6 (0.6)	0.5 (0.1¶)	0.3 (0.1¶)	4.7 (1.4)
2.10	0.3 (0.1¶)	9.2 (3.2)	1.8 (0.3)	43 (9)	3 (3)	0.4 (0.1¶)	8 (6)	0.1¶ (0.1¶)	10.5 (2.9)	1.1 (0.5)	0.4 (0.1¶)	0.2 (0.1¶)	2.7 (0.3)
2.30	0.2 (0.1¶)	7.9 (6.2)	2.1 (1.1)	41 (18)	25 (15)	0.6 (0.1¶)	8 (6)	0.1¶ (0.1¶)	7.7 (4.1)	0.3 (0.1¶)	0.3 (0.2)	0.2 (0.1¶)	2.3 (0.7)
2.50	0.2 (0.1¶)	3.3 (1.3)	3.6 (2.6)	31 (3)	16 (9)	0.5 (0.1¶)	11 (6)	0.1¶ (0.1¶)	5.5 (1.1)	0.5 (0.1¶)	0.3 (0.1¶)	0.1¶ (0.1¶)	2.3 (0.5)
2.70	0.1¶ (0.1¶)	2.2 (1.8)	0.5 (0.1¶)	29 (1)	1 (1)	0.6 (0.1¶)	5 (4)	0.1¶ (0.1¶)	3.1 (1.6)	0.4 (0.1¶)	0.1¶ (0.1¶)	0.1¶ (0.1¶)	2.0 (0.4)
2.90	0.1¶ (0.1¶)	2.0 (1.7)	1.3 (0.9)	28 (9)	ND#	0.6 (0.1¶)	4 (2)	0.1¶ (0.1¶)	4.8 (3.2)	0.5 (0.3)	0.2 (0.1¶)	0.1¶ (0.1¶)	2.0 (0.9)
3.15	0.1¶ (0.1¶)	2.0 (1.2)	1.3 (0.6)	28 (2)	ND	0.5 (0.1¶)	4 (3)	0.1¶ (0.1¶)	4.7 (1.7)	0.4 (0.1¶)	0.2 (0.1¶)	0.1¶ (0.1¶)	1.9 (0.4)
3.45	0.1¶ (0.1¶)	2.0 (1.4)	1.7 (0.1¶)	29 (6)	ND	0.6 (0.1¶)	7 (3)	0.1¶ (0.1¶)	3.6 (1.2)	0.8 (0.6)	0.2 (0.1¶)	0.1¶ (0.1¶)	2.9 (1.2)
3.75	0.1¶ (0.1¶)	0.4 (0.2)	0.4 (0.4)	26 (7)	ND	0.6 (0.1¶)	4 (2)	0.1¶ (0.1¶)	1.8 (1.2)	0.2 (0.1¶)	0.1¶ (0.1¶)	0.1¶ (0.1¶)	1.1 (0.1¶)

† Average depth of dissected core beneath the lagoon floor.
‡ Cation exchange capacity.
§ Numbers in parentheses represent the standard errors of the mean (SEM).
¶ Value ≤ 0.1.
# No detection.

Table 3. Lagoon liquor constituent profiles beneath a 17-yr-old, 0.1-ha cattle-feedlot runoff lagoon (Cattle 3) located in Kansas.

Depth†	Organic C	Olsen P	Cl	Total N	NO_3–N	NH_4–N	NH_4	Ca	Mg	K	Na	CEC‡
m	g kg^{-1}	mg kg^{-1}					cmol$_c$ kg^{-1}					
0.05	4.0 (0.7)§	85.4 (31.2)	185 (29)	861 (157)	0.5 (0.1¶)	275 (129)	2.0 (1.0)	9.8 (3.9)	5.7 (0.7)	5.6 (2.2)	1.3 (0.1¶)	27.5 (1.7)
0.15	4.0 (0.9)	77.4 (29.9)	179 (30)	771 (163)	0.5 (0.1¶)	232 (117)	1.7 (0.8)	11.4 (5.0)	6.1 (0.9	4.5 (2.1)	1.4 (0.2)	28.0 (3.0)
0.25	3.8 (1.0)	78.4 (24.3)	176 (30)	738 (181)	0.7 (0.2)	173 (90)	1.2 (0.6)	15.0 (5.7)	5.6 (1.4)	4.3 (1.9)	1.2 (0.3)	27.1 (4.4)
0.35	2.9 (0.6)	58.8 (19.8)	169 (19)	510 (125)	0.6 (0.2)	125 (68)	0.9 (0.5)	13.5 (6.3)	4.9 (1.7)	3.3 (1.8)	1.1 (0.5)	25.1 (6.0)
0.45	2.7 (0.4)	50.1 (17.1)	178 (23)	387 (89)	0.7 (0.2)	94 (52)	0.7 (0.4)	15.2 (11.7)	6.8 (3.0)	2.2 (1.0)	2.0 (1.0)	22.5 (6.7)
0.55	2.2 (0.5)	46.6 (14.1)	176 (29)	361 (87)	0.6 (0.2)	82 (43)	0.6 (0.3)	11.2 (7.1)	3.7 (1.9)	2.2 (1.1)	1.1 (0.7)	21.8 (7.3)
0.65	2.5 (0.3)	39.5 (6.8)	153 (20)	351 (10)	0.7 (0.2)	76 (38)	0.5 (0.3)	8.1 (5.5)	4.5 (1.6)	1.7 (0.6)	1.4 (0.6)	20.8 (6.8)
0.75	1.8 (0.5)	39.9 (11.5)	134 (15)	224 (72)	0.5 (0.1¶)	46 (72)	0.3 (0.3)	6.8 (4.9)	4.0 (1.6)	1.4 (0.8)	1.3 (0.6)	19.4 (7.6)
0.85	1.5 (0.4)	39.5 (10.8)	131 (12)	185 (66)	0.8 (0.3)	36 (24)	0.3 (0.2)	6.6 (5.0)	3.4 (1.5)	1.3 (0.7)	1.1 (0.5)	15.6 (6.3)
0.95	0.9 (0.3)	20.4 (5.7)	111 (25)	91 (41)	0.6 (0.1¶)	28 (16)	0.2 (0.1¶)	4.0 (2.8)	1.3 (0.8)	0.7 (0.2)	0.5 (0.3)	10.0 (4.0)
1.05	0.5 (0.1¶)	15.6 (4.9)	125 (25)	52 (4)	0.7 (0.3)	17 (7)	0.1¶ (0.1¶)	2.7 (2.1)	1.6 (0.8)	0.4 (0.1¶)	0.6 (0.3)	8.0 (3.1)
1.15	0.8 (0.3)	14.9 (2.8)	147 (32)	85 (21)	0.6 (0.1¶)	20 (10)	0.1¶ (0.1¶)	2.5 (1.5)	1.1 (0.3)	0.5 (0.2)	0.5 (0.2)	6.8 (2.2)
1.25	0.8 (0.4)	11.8 (3.4)	145 (18)	74 (38)	0.5 (0.1¶)	19 (8)	0.1¶ (0.1¶)	1.9 (0.8)	0.9 (0.1¶)	0.8 (0.2)	0.5 (0.1¶)	5.8 (1.8)
1.35	0.5 (0.2)	11.1 (5.5)	144 (12)	45 (16)	0.4 (0.2)	20 (11)	0.1¶ (0.1¶)	1.0 (0.3)	0.5 (0.1¶)	0.4 (0.2)	0.3 (0.1¶)	4.8 (2.2)
1.45	0.9 (0.6)	31.0 (25.6)	166 (68)	104 (86)	0.9 (0.4)	49 (44)	0.4 (0.3)	2.2 (1.1)	0.9 (0.4)	1.0 (0.8)	0.5 (0.2)	4.0 (2.0)
1.55	0.2 (0.1¶)	5.9 (0.2)	107 (27)	46 (24)	0.5 (0.1¶)	6 (3)	0.1¶ (0.1¶)	0.7 (0.5)	0.3 (0.1¶)	0.2 (0.1¶)	0.2 (0.1¶)	2.3 (0.9)
1.65	0.2 (0.1¶)	4.6 (0.1)	93 (47)	29 (29)	0.6 (0.3)	2 (1)	0.1¶ (0.1¶)	0.6 (0.6)	0.3 (0.1¶)	0.1¶ (0.1¶)	0.2 (0.1¶)	1.5 (0.2)

† Average depth of dissected core beneath the lagoon floor.
‡ Cation exchange capacity.
§ Numbers in parentheses represent the standard errors of the mean (SEM).
¶ Value ≤ 0.1.

lagoons were highly correlated with the concentrations of clay at respective depths ($y = 0.65 + 0.06x$, $r^2 = 0.93$, $n = 74$). Therefore, the CEC of the soils underlying all three cattle lagoons decreased as the clay concentrations decreased (Tables 1–3, Fig. 1). The CEC values under the swine lagoon were highly variable below the 1-m depth and were as high as 54 cmol$_c$ kg^{-1} (centimole charge of saturating cation per kilogram) (Table 4). A reduction in the CEC of soils underlying lagoons is undesirable and limits the potential exchange sites that are necessary to adsorb downward-moving NH_4^+. DeSutter and Pierzynski (2005) have recently evaluated the effectiveness of adding bentonite and zeolite materials to lagoon-liner soils to help increase the effective CEC of the soil mixture and also increase the selectivity for NH_4^+. They concluded that additions of bentonite and zeolite could effectively increase the CEC of native soils but additions of these amendments may not increase the selectivity of these soils for NH_4^+ over other cations.

The pH values of the soils under the three cattle lagoons were generally greater than 8.2 (Fig. 2), the pH of calcareous soil (Lindsay, 1979). However, Cattle 3 was determined not to be calcareous whereas Cattle 1 and Cattle 2 were determined to be calcareous (Tables 1 and 2). Soil pH could have been affected by downward-moving lagoon liquor, which is reported to range in swine and cattle lagoons between 6.5 to 8.5 and 7.1 to 8.1, respectively (Ham, 2002; Ham and DeSutter, 2000). The soil pH of the swine lagoon was variable and ranged from 7.4 near the surface to 8.4 at about 1 m (Fig. 2). Soils under animal-waste lagoons investigated by Miller et al. (1976), Parker et al. (1995), and Perschke and Wright (1998) also indicate pH values near or above 8.0 but one cannot definitively state whether the soils investi-

Table 4. Lagoon liquor constituent profiles beneath a 25-yr-old, 0.1-ha swine lagoon located in Kansas.

Depth†	Organic C	$CaCO_3$	Olsen P	Cl	Total N	NO_3–N	NH_4–N	NH_4	Ca	Mg	K	Na	CEC‡
m	g kg^{-1}		mg kg^{-1}					cmol$_c$ kg^{-1}					
0.05	8.7 (2.8)§	ND¶	244.8 (8.4)	43 (9)	2092 (337)	1.6 (0.4)	1139 (82)	8.1 (0.6)	3.0 (0.6)	1.8 (0.3)	3.9 (0.4)	0.3 (0.1#)	17.2 (1.7)
0.15	7.3 (2.5)	ND	153.2 (17.5)	44 (12)	1703 (224)	1.0 (0.1#)	1118 (104)	7.9 (0.7)	3.1 (0.5)	1.7 (0.2)	4.1 (0.5)	0.3 (0.1#)	17.3 (1.7)
0.25	4.8 (1.9)	ND	84.6 (25.8)	32 (2)	1562 (202)	1.0 (0.1#)	1004 (103)	7.2 (0.7)	2.7 (0.4)	1.4 (0.1#)	3.8 (0.3)	0.3 (0.1#)	16.0 (1.1)
0.38	5.4 (1.6)	–††	40.0 (19.9)	33 (2)	1383 (150)	0.7 (0.1#)	897 (54)	6.4 (0.4)	2.8 (0.4)	1.3 (0.2)	2.9 (0.5)	0.3 (0.1#)	16.2 (1.5)
0.53	3.5 (0.6)	ND	33.9 (10.7)	26 (3)	903 (78)	0.7 (0.1#)	683 (77)	4.9 (0.6)	2.6 (0.3)	1.2 (0.2)	2.6 (0.4)	0.2 (0.1#)	11.9 (1.4)
0.75	3.3 (1.1)	ND	67.3 (38.0)	26 (4)	903 (227)	1.4 (0.6)	635 (149)	4.5 (1.1)	3.4 (0.8)	1.5 (0.3)	2.3 (0.6)	0.2 (0.1#)	11.3 (2.9)
1.05	1.2 (0.2)	ND	14.3 (3.0)	29 (2)	410 (76)	0.9 (0.2)	258 (39)	1.8 (0.3)	5.2 (2.2)	1.7 (0.6)	0.8 (0.4)	0.1# (0.1#)	9.9 (2.8)
1.35	0.9 (0.2)	ND	10.1 (0.9)	29 (3)	324 (132)	0.6 (0.1#)	231 (102)	1.6 (0.7)	5.1 (1.2)	1.6 (0.4)	0.4 (0.3)	0.2 (0.1#)	9.6 (2.2)
1.65	0.9 (0.4)	–‡‡	12.9 (3.4)	30 (2)	344 (128)	0.7 (0.1#)	216 (76)	1.5 (0.5)	8.5 (2.8)	2.3 (0.7)	0.4 (0.3)	0.3 (0.1#)	12.2 (3.4)
1.95	0.9 (0.3)	–§§	13.2 (9.2)	52 (13)	243 (59)	0.9 (0.2)	143 (45)	1.0 (0.3)	28.1 (11.7)	4.4 (1.3)	0.6 (0.4)	0.3 (0.1#)	23.9 (9.7)
2.25	0.5 (0.1#)	–¶¶	5.8 (2.9)	44 (6)	352 (170)	1.2 (0.5)	118 (88)	0.8 (0.6)	25.0 (11.2)	4.0 (1.5)	0.6 (0.3)	0.4 (0.1#)	39.1 (9.8)
2.55	0.6 (0.4)	–##	14.8 (3.2)	30 (1)	297 (83)	1.0 (0.3)	156 (38)	1.1 (0.3)	16.5 (4.1)	2.3 (0.6)	0.5 (0.3)	0.3 (0.1#)	14.2 (3.2)
2.85	0.3 (0.2)	–†††	19.0 (12.5)	42 (7)	231 (72)	1.2 (0.2)	66 (30)	0.5 (0.2)	24.8 (10.7)	3.3 (1.0)	1.6 (1.4)	0.3 (0.1#)	36.2 (8.0)
3.15	0.3 (0.2)	–‡‡‡	3.1 (0.6)	42 (4)	262 (60)	2.2 (0.3)	31 (13)	0.2 (0.1#)	52.5 (0.8)	6.9 (0.4)	1.1 (0.4)	0.3 (0.1#)	54.0 (1.3)

† Average depth of dissected core beneath the lagoon floor.
‡ Cation exchange capacity.
§ Numbers in parentheses represent the standard errors of the mean (SEM).
¶ No detection.
# Value ≤ 0.1.
†† $CaCO_3$ ranged from no detection to 18.6 g kg^{-1}.
‡‡ $CaCO_3$ ranged from no detection to 3.4 g kg^{-1}.
§§ $CaCO_3$ ranged from no detection to 82.5 g kg^{-1}.
¶¶ $CaCO_3$ ranged from no detection to 30.9 g kg^{-1}.
$CaCO_3$ ranged from no detection to 7.1 g kg^{-1}.
††† $CaCO_3$ ranged from no detection to 40.4 g kg^{-1}.
‡‡‡ $CaCO_3$ ranged from no detection to 57.2 g kg^{-1}.

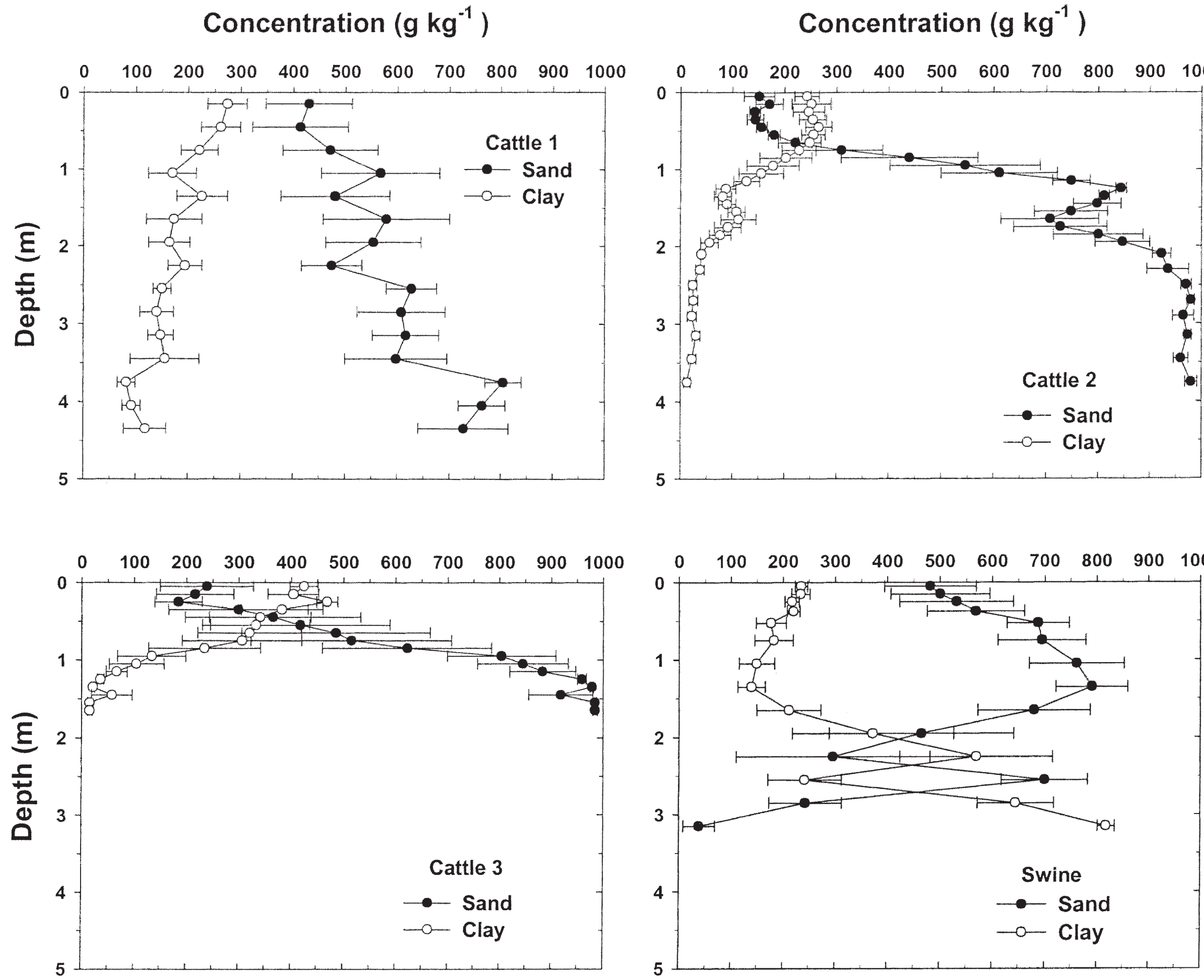

Fig. 1. Sand and clay concentrations beneath three cattle-feedlot runoff lagoons and one swine-waste lagoon. Bars indicate the standard errors of the mean.

gated by these authors are calcareous based on the presented data and/or soils descriptions. Although not reported, the standard errors of the mean (SEM) of the pH values in Fig. 2 were generally less than 0.2.

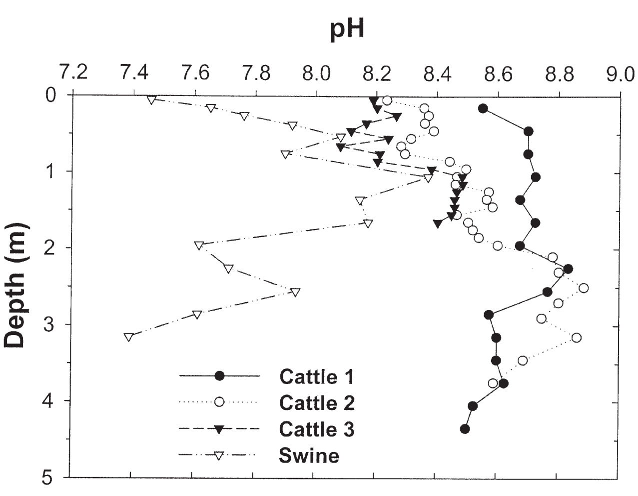

Fig. 2. pH profiles beneath three cattle-feedlot runoff retention lagoons and one swine-waste lagoon.

Organic Carbon

Organic C values in Cattle 1, Cattle 2, and Cattle 3 were 5.2, 3.0, and 4.0 g kg^{-1} near the surface and decreased to less than 0.5 g kg^{-1} below 2.55, 1.85, and 1.45 m, respectively (Tables 1–3). Organic C concentrations were greatest in the upper soil under the swine lagoon (8.7 g kg^{-1}) and decreased to less than 0.5 g kg^{-1} below a depth of 2.55 m. These levels of organic C, typically less than 10 g kg^{-1}, were also observed under lagoons sampled by Miller et al. (1976), Parker et al. (1995), and Perschke and Wright (1998). Overall, movement of organic C was evident, with concentrations greatest at the surface soils and decreasing to less than 0.5 g kg^{-1} at the bottom of the profile. Movement of organic C will be a function of lagoon seepage rate, concentration of organic C in the lagoon liquor, liner construction, the conversion of the organic C to CH_4 and CO_2 through anaerobic digestion, and the fraction of the organic C in the liquor that is soluble or present as small enough particles to move through the liner and underlying soil.

Nitrogen

Total N concentrations of up to 861 mg kg^{-1} were observed in the upper profiles of the cattle lagoons with concentrations decreasing to less than 80 mg kg^{-1} at the maximum-sampled depths (Tables 1–3). This trend of high total N concentrations in the upper soil followed by lower concentrations of total N in the lowest depths indicates that N has moved from the lagoon liquor and into the underlying soil. In Cattle 1 and Cattle 3, movement of N extended below our sampling abilities and concentrations were above expected background levels for total N at 4.35 and 1.65 m, respectively (Tables 1 and 3). Total N per area under Cattle 1, Cattle 2, and Cattle 3, assuming a bulk density of 1300 kg m^{-3}, was 1230, 750, and 630 g m^{-2}, respectively.

Ammonium N made up 59, 32, and 26% of the total N per area under Cattle 1, Cattle 2, and Cattle 3, respectively. Ammonium N concentrations in the upper soil profiles of Cattle 1, Cattle 2, and Cattle 3 were 378, 361, and 275 mg kg^{-1}, respectively, and declined to 25 mg kg^{-1} in Cattle 1 and less than 5 mg kg^{-1} in Cattle 2 and Cattle 3 in the lowermost samples (Tables 1–3). Nitrate N concentrations found under the cattle lagoons were generally less than 5 mg kg^{-1} (Tables 1–3). However, greater NO_3–N concentrations were observed in the uppermost samples of Cattle 1 and Cattle 2 indicating that some conversion of organic N and/or NH_4–N to NO_3–N had likely occurred. Cattle 1 and Cattle 2 were void of wastes and thus the surface soils in these lagoons were exposed to the atmosphere for at least two months before sampling. Migration of NO_3–N from the lagoon liquor into the underlying soil was not likely based on the lack of NO_3–N reported to be in cattle and swine lagoon liquors (Barker et al., 2001; DeRouchey et al., 2002; Ham, 2002; Ham and DeSutter, 1999, 2000). Results of NH_4–N and NO_3–N movement from the cattle lagoons are similar to those presented by Parker et al. (1995) and Perschke and Wright (1998), in which the greatest NH_4–N concentration was observed in the upper soil profile and concentrations decreased with increasing depth. The difference between the total N and the inorganic N fractions (NH_4–N and NO_3–N) was assumed to be organic N. Thus, the amounts of organic N per area under Cattle 1, Cattle 2, and Cattle 3 were 480, 500, and 460 g m^{-2}, respectively.

The swine lagoon had the greatest total N concentration in the uppermost soil (2092 mg kg^{-1}) of all four lagoons (Table 4). Total N concentrations decreased with depth to 262 mg kg^{-1} near the bottom of the profile. Total N per area under the swine lagoon, assuming a bulk density of 1300 kg m^{-3}, was 2450 g m^{-2}, which is about two times more than the highest cattle lagoon, Cattle 1. As with the concentrations of total N, NH_4–N concentrations were greatest in the uppermost samples (1139 mg kg^{-1}) and decreased with increasing depth to 31 mg kg^{-1} in the lowermost sample. Ammonium N accounted for 59% of the total N per area under the swine lagoon. Nitrate N concentrations under the swine lagoon were similar to those of Cattle 3 with values less than 5 mg kg^{-1} throughout the sampling depths. Organic N concentrations were about 950 and 231 mg kg^{-1} in the uppermost and lowermost samples, respectively, and accounted for about 40% of the total N per area under the swine lagoon. Other research has shown that high concentrations of NH_4–N exist in soils directly beneath swine lagoons and that these concentrations generally decrease as depth below the lagoons increases (Maule and Fonstad, 1996; Miller et al., 1976).

Overall, the soil underlying the swine lagoon had as much as two times more total N per unit area than soil beneath Cattle 1 (2.4 and 1.2 kg m^{-2}, respectively), which is partly explained by the swine lagoon being in operation for 22 yr, while Cattle 1 was in operation for only 11 yr. More N under the swine lagoon may also be partially explained by the fact that swine lagoons typically have greater concentrations of N in the lagoon liquor than do cattle lagoons (Ham, 1999, 2002; Ham and DeSutter, 2000). The presence of large quantities of both NH_4–N and organic N under the lagoons presents a potential threat to ground water resources should this N be converted to NO_3–N via mineralization and nitrification. Conditions conducive to mineralization and nitrification could develop if lagoons were to stop receiving waste and the liner became aerobic, as in the case of Cattle 1 and Cattle 2. The potential for nitrate leaching should be considered in the implementation of lagoon closure procedures.

Phosphorus

Phosphorus concentrations in digested Olsen's extracts were slightly higher or equal to those in undigested extracts (data not shown), suggesting that extractable organic P forms were only minor components of the P extracted with the sodium bicarbonate solution. This is in general agreement with reports that indicate that much of the P in manures is present in inorganic forms (Sharpley and Moyer, 2000). Data from the undigested Olsen's extracts are discussed below.

Olsen P concentrations in the uppermost soil under Cattle 1, Cattle 2, and Cattle 3 were 71, 131, and 85 mg kg^{-1}, respectively, and declined to concentrations of less than 5 mg kg^{-1} in the lowermost samples of each lagoon (Tables 1–3). The extractable P (Bray) values reported in Parker et al. (1995) were similar to the results presented here; the range from the lower and upper profiles was between 20 and 120 mg kg^{-1}. Eghball et al. (1996) reported P movement, as measured with the Olsen extraction procedure, down to 1.8 m in soils heavily amended with cattle manure.

Extractable Olsen P was 245 mg kg^{-1} in the top 10 cm of soil under the swine lagoon and was less than 5 mg kg^{-1} in the lowermost sampling depth (Table 4). Higher Olsen P levels under the swine lagoon may be the result of swine lagoon liquors having about three times more total P than cattle lagoon liquors (150 vs. 59 mg L^{-1}, respectively) (Ham, 2002). Phosphorus extracted from soil underlying four swine lagoons in Canada with a dilute salt solution indicated much less downward movement than the values reported for the swine lagoon reported here, with values only as high as 16.6 mg kg^{-1} in the uppermost 0.1 m (Miller et al., 1976). The primary concern with P movement below lagoons would be the possible impacts on surface waters. This could occur if leached P came into contact with ground water, which then contributed to surface flow, a situation that is possible if a lagoon were sited near a surface water body.

Cation Influence on Ammonium Ion Adsorption

The downward movement of NH_4^+ from the lagoon liquor will be a function of the whole-lagoon seepage rate, the CEC, mineralogy, and bulk density of the underlying soil, the concentration of NH_4^+ and other cations (i.e., Ca^{2+}, Mg^{2+}, K^+, and Na^+) in the lagoon liquor, the amount of time the lagoon has liquor present in it, and the competition of cations in the lagoon liquor for soil exchange sites. Ideally, soil liners would be designed so that the majority of the exchange sites would be occupied by NH_4^+ and thus decrease the depth of soil needed to adsorb 100% of the downward-moving NH_4^+ (DeSutter and Pierzynski, 2005). Using the CEC values from the top 0.5 m of soil underlying the lagoons, as determined by the method outlined in Sumner and Miller (1996), NH_4^+ was present on about 22, 9, 5, and 44% of the soil exchange sites of the Cattle 1, Cattle 2, Cattle 3, and the swine lagoon, respectively (Tables 1–4). The greater fraction of exchange sites occupied by NH_4^+ on the swine lagoon soil may have been a result of swine lagoons typically having about five to six times more NH_4–N in the lagoon liquor than do cattle lagoons, coupled with similar concentrations of Ca, Mg, K, and Na in swine and cattle liquors (Ham, 2002; Ham and DeSutter, 2000). DeSutter and Pierzynski (2005) have shown that the predicted percentage of exchange sites occupied by NH_4^+ in two natural soils, when in contact with liquors from swine and cattle lagoons containing Ca^{2+}, K^+, and NH_4^+, were up to 55% with swine and up to 25% with cattle lagoon liquors.

Other variables that may affect the downward movement of NH_4^+ may be the influence of Ca^{2+} and/or Mg^{2+} released from calcareous or gypsiferous subsoils and/or liner soils by the downward-moving lagoon liquor or the influence of organic C on the CEC and cation selectivity properties of the soil material (Chung and Zasoski, 1994; Fletcher et al., 1984; Goulding, 1981). The method used to extract cations from the lagoon soils may have helped dissolve carbonates in Cattle 1 and Cattle 2 and, in combination with the Ca^{2+} in the lagoon liquor, increased Ca^{2+} concentrations in the soil ($cmol_c\ kg^{-1}$) beyond the soil CEC (Tables 1 and 2). The elevated levels of soil Ca^{2+} (lagoon liquor plus dissociated Ca^{2+}) may then compete with NH_4^+ for soil exchange sites and thus increase the amount of soil needed to adsorb downward-moving NH_4^+.

Chloride

The concentrations of Cl in the uppermost soils under the Cattle 1, Cattle 2, Cattle 3, and the swine lagoon were 8, 147, 185, and 43 mg kg^{-1}, respectively (Tables 1–4). In soils under both Cattle 1 and the swine lagoon the concentrations of Cl were fairly uniform with increasing depth while in soils under Cattle 2 and Cattle 3 the concentration of Cl steadily decreased as sampling depth increased. Under all four lagoons, measurable amounts of Cl were present in the lowermost samples indicating that the background levels of Cl were high enough for detection with the methods used to determine Cl or that the plume of lagoon liquor had moved beyond our sampling abilities.

Sampling Variability

Although the lagoons were each sampled in the center of four equally spaced sections, SEM values indicate that a high degree of variation was present within sampling depths within each lagoon (Tables 1–4). For example, SEM values of the total N in the uppermost samples of cattle lagoons were up to 27% of the mean values and in the lowermost samples were up to 100% of the mean values (Tables 1–3). The cattle lagoons investigated in this study were mainly used to store rainfall runoff from the cattle holding pens and thus the amount of effluent that entered the lagoons was dictated by rainfall patterns and runoff volumes. Therefore, liquor may have ponded in the low areas of the lagoons for longer periods of time or not have entered lagoons at all for long durations. Although not confirmed, the length of time that liquor was in Cattle 1 vs. Cattle 2 may help explain why the amount of total N under Cattle 1 was about two times higher than what was under Cattle 2. Parker et al. (1995) showed greater concentrations of N on one side of a 22-yr-old cattle runoff lagoon than in other parts of the lagoon. Although not specifically stated in the Parker et al. (1995) study, this area of higher N concentrations may have been a low spot where waste collected for extended periods of time and/or an area of increased seepage rate.

Swine lagoons typically receive enough effluent throughout the year so that the lagoon floor is completely covered with liquor. The SEM values associated with the uppermost 1 m of soil of the total N concentrations under the swine lagoon were between 9 and 25% of the mean values and were generally one-half times less than the SEM values for total N under the cattle lagoons (Tables 1–4). However, starting at the 1.35-m sampling depth under the swine lagoon, the total N SEM values increased as the variation in clay content under the lagoon also increased. Thus, variations in subsoil structure may also influence the variations in chemical concentrations under lagoons. Although the discussion of this section has focused on total N, variations in the concentrations of all the measured parameters existed in all of the lagoons.

Single-core assessments of the lagoon liquor constituent concentrations under animal waste lagoons may not be adequate when evaluating the concentrations and masses of constituents beneath lagoons or the depth that these constituents may have leached. Variations in the mobility of the constituents within and between different lagoons will be influenced by the subsoil structure, variations in lagoon design and construction, spatial variations in lagoon seepage, changes in concentrations of lagoon liquor constituents over time, and length of time that lagoons have liquor in them. The nonuniform movement of lagoon liquor constituents into the underlying soil should be addressed when lagoon closure and remediation plans are implemented.

CONCLUSIONS

Results from soil samples collected from under three cattle-feedlot runoff retention lagoons and one swine-waste lagoon indicate the downward movement of lagoon-liquor constituents. The most definable constituents were NH_4–N and organic N. Ammonium N made up about 59, 32, 26, and 59% of the total N per area under the three cattle lagoons and swine lagoon, respectively. Movement of N out of lagoons into the underlying soils is undesirable due to the potential conversion of N, through mineralization and/or nitrification, to the more mobile NO_3–N when the lagoon soils are exposed to the atmosphere. Although differing charge concentrations of cations were detected under all lagoons, NH_4^+ was present on about 22, 9, 1, and 44% of the exchange sites of the upper 0.5 m of soil under the three cattle lagoons and swine lagoon, respectively. The downward movement of NH_4–N will be a function of the whole-lagoon seepage rate, the concentrations and types of cations in the liquor and soil, and the mineralogy and subsequent selectivity of the underlying soil for NH_4^+.

Lagoons used to hold animal wastes are commonly constructed of differing sizes and are commonly managed under differing strategies. Given these two variables, lagoon liquor constituent concentrations may be vastly different between and within the same species type (DeRouchey et al., 2002; Ham, 2002). Thus, caution should be used when soil-sampling results from one lagoon are extrapolated to other lagoons without past knowledge of lagoon design and construction, species type, lagoon liquor concentrations, and lagoon and animal management strategies.

Evidence suggests the movement of N, P, and Cl, beyond the depth of coring. The total removal of these lagoon liquor constituents from the soils underlying these lagoons may be impractical. Reclamation possibilities include phytoremediation (Zhu and Kirkham, 2002, 2003) or removal of the soil through excavation and earthmoving (Ham, 2002). Although both of these possibilities are feasible, the time and cost needed to achieve satisfactory results may be overwhelming and expensive. Alternative storages for swine waste are steel tanks, concrete tanks, or plastic-lined lagoons (Ham and DeSutter, 2000), but no feasible alternative exists for holding cattle-feedlot runoff. Thus, the popularity of soil-lined lagoons remains strong. By following the site-specific design standards proposed by Ham and DeSutter (2000) and/or constructing lagoon liners with soils that may selectively retain liquor constituents (i.e., NH_4–N) (DeSutter and Pierzynski, 2005), the downward movement of ground water polluting chemicals may be reduced or eliminated.

REFERENCES

Adriano, D.C., and H.E. Doner. 1982. Bromine, chlorine, and fluorine. p. 449–483. *In* A.L. Page, R.H. Miller, and D.R. Keeney (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Baker, J.L., T.D. Glanville, S.W. Melvin, and L.E. Shiers. 2000. Soil sampling and analysis around earthen waste storage structures in Iowa. ASAE Paper 004120. Am. Soc. Agric. Eng., St. Joseph, MI.

Barker, J.C., J.P. Zublena, and F.R. Walls. 2001. Animal and poultry manure production and characterization: Table 23. Swine anaerobic lagoon liquid characteristics [Online]. Available at www.bae.ncsu.edu/programs/extension/manure/awm/program/barker/a&pmp&c/sll.htm (verified 22 Feb. 2005). North Carolina State Univ., Raleigh.

Cates, K.J. 1983. The movement of selected waste constituents through the earthen liner of a manure holding pond. M.S. thesis. Univ. of Wisconsin, Madison.

Chung, J.B., and R.J. Zasoski. 1994. Ammonium-potassium and ammonium-calcium exchange equilibria in bulk and rhizosphere soil. Soil Sci. Soc. Am. J. 58:1368–1375.

Ciravolo, T.G., D.C. Martens, D.L. Hallock, E.R. Collins, Jr., E.T. Kornegay, and H.R. Thomas. 1979. Pollutant movement to shallow ground water tables from anaerobic swine waste lagoons. J. Environ. Qual. 8:126–130.

Crooke, W.M., and W.E. Simpson. 1971. Determination of ammonium in Kjeldahl digests of crops by an automated procedure. J. Sci. Food Agric. 22:9–10.

Culley, J.L.B., and P.A. Phillips. 1989. Retention and loss of nitrogen and solids from unlined earthen manure storages. Trans. ASAE 32:677–683.

DeRouchey, J.M., R.D. Goodband, J.L. Nelssen, M.D. Tokach, S.S. Dritz, and J.P. Murphy. 2002. Nutrient composition of Kansas swine lagoons, hoop barn manure. J. Anim. Sci. 80:2051–2061.

DeSutter, T.M., and G.M. Pierzynski. 2005. Evaluation of soils for use as liner materials: A soil chemistry approach. J. Environ. Qual. 34:951–952.

Eghball, B., G.D. Binford, and D.D. Baltensperger. 1996. Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application. J. Environ. Qual. 25:1339–1343.

Fletcher, P., G. Sposito, and C.S. LeVesque. 1984. Sodium-calcium-magnesium exchange reactions on a montmorillonitic soil: I. Binary exchange reactions. Soil Sci. Soc. Am. J. 48:1016–1021.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Glanville, T.D., J.L. Baker, S.W. Melvin, and M.M. Agua. 2001. Measurement of leakage from earthen manure storage structures in Iowa. Trans. ASAE 44:1609–1616.

Goulding, K.W.T. 1981. Potassium retention and release in Rothamsted and Saxmundhum soils. J. Sci. Food Agric. 32:667–670.

Ham, J.M. 1999. Measuring evaporation and seepage losses from lagoons used to contain animal waste. Trans. ASAE 42:1303–1312.

Ham, J.M. 2002. Seepage losses from animal waste lagoon: A summary of a four-year investigation in Kansas. Trans. ASAE 45:983–992.

Ham, J.M., and T.M. DeSutter. 1999. Seepage losses and nitrogen export from swine-waste lagoons: A water balance study. J. Environ. Qual. 28:1090–1099.

Ham, J.M., and T.M. DeSutter. 2000. Toward site-specific design standards for animal-waste lagoons: Protecting ground water quality. J. Environ. Qual. 29:1721–1732.

Huffman, R.L. 2004. Seepage evaluation of older swine lagoons in North Carolina. Trans. ASAE 47:1507–1512.

Huffman, R.L., and P.W. Westerman. 1995. Estimated seepage losses from established swine waste lagoons in the lower coastal plain of North Carolina. Trans. ASAE 38:449–453.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen—Inorganic forms. p. 643–698. *In* A.L. Page, R.H. Miller, and D.R. Keeney (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Lindsay, W.L. 1979. Chemical equilibria in soils. John Wiley & Sons, New York.

Maule, C.P., and T.A. Fonstad. 1996. Ion movement immediately beneath earthen hog manure storages: How much, how deep, and how fast. ASAE Paper 962049. Am. Soc. Agric. Eng., St. Joseph, MI.

McCurdy, M., and K. McSweeney. 1993. The origin and identification of macropores in an earthen-lined dairy manure storage basin. J. Environ. Qual. 22:148–154.

Miller, M.H., J.B. Robinson, and D.W. Gallagher. 1976. Accumulation of nutrients in soil beneath hog manure lagoons. J. Environ. Qual. 5:279–282.

Nelson, D.W., and J.M. Bremner. 1972. Preservation of soil samples for inorganic nitrogen analyses. Agron. J. 64:196–199.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. U.S. Gov. Print. Office, Washington, DC.

Parker, D.B., J.A. Nienaber, D.E. Eisenhauer, and D.D. Schulte. 1995. Unsaturated seepage from a feedlot runoff storage pond. ASAE Paper 951765. Am. Soc. Agric. Eng., St. Joseph, MI.

Perschke, S.P., and P.E. Wright. 1998. Evaluation of soil under an earthen manure storage pond. ASAE Paper 982145. Am. Soc. Agric. Eng., St. Joseph, MI.

Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29:1462–1469.

Suarez, D.L. 1996. Beryllium, magnesium, calcium, strontium, and barium. p. 575–601. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Sumner, M.E., and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. p. 1201–1229. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

USEPA. 2002. List of drinking water contaminants and MCLs [Online]. Available at www.epa.gov/safewater/mcl.html#mcls (verified 22 Feb. 2005). USEPA, Washington, DC.

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from the soil. Soil Sci. Soc. Am. Proc. 29:677–678.

Westerman, P.W., R.L. Huffman, and J.S. Feng. 1995. Swine-lagoon seepage in sandy soil. Trans. ASAE 38:1749–1760.

Withers, P.J.A., H.G. McDonald, K.A. Smith, and C.G. Chumbley. 1998. Behavior and impact of cow slurry beneath a storage lagoon: 1. Groundwater contamination 1975-1982. Water Air Soil Pollut. 107:35–49.

Zhu, L., and M.B. Kirkham. 2002. Initial crop growth in soil collected from a closed animal waste lagoon. Bioresour. Technol. 87:7–15.

Zhu, L., and M.B. Kirkham. 2003. Plant remediation of soil beneath an abandoned animal waste lagoon. J. Sustain. Agric. 22:119–133.